

# Extreme Superstarclusters

Paul P. van der Werf <sup>★</sup> and Leonie Snijders

Leiden Observatory, P.O. Box 9513, NL - 2300 RA Leiden, The Netherlands

Received 2006 month day; accepted 2006 month day

**Abstract** The presence of superstarclusters is a characteristic feature of starburst galaxies. We examine the properties of star forming regions and young star clusters in various environments, ranging from common to extreme. We then discuss new high spatial resolution mid-infrared imaging and spectroscopy of extreme superstarclusters in the obscured region of the Antennae (NGC 4038–4039). We find that the PAH emission in this region is not dominated by the superstarclusters but is mostly diffuse. Emission line ratios found in our high spatial resolution data differ significantly from those in larger apertures, strongly affecting the derived results.

**Key words:** galaxies: star clusters — galaxies: starburst — galaxies: individual (NGC 4038–4039)

## 1 SCALING STARBURSTS

Starburst galaxies cover an enormous range in luminosity. At the low luminosity end the small starforming dwarf galaxies such as the Small and Large Magellanic Clouds have  $L_{\text{IR}} = 7 \cdot 10^7 L_{\odot}$  and  $L_{\text{IR}} = 7 \cdot 10^8 L_{\odot}$ . More distant infrared-bright dwarf galaxies have typically  $L_{\text{IR}} \sim 3 \cdot 10^9 L_{\odot}$ . Well-studied nearby starbursts such as NGC 253 and M82 have  $L_{\text{IR}} = 3 \cdot 10^{10} L_{\odot}$  and  $6 \cdot 10^{10} L_{\odot}$  (luminosities are from Sanders et al. 2003). At higher luminosities, we have the luminous infrared galaxies (LIRGs) with  $L_{\text{IR}} > 10^{11} L_{\odot}$  (e.g., the Antennae, NGC 4038–4039), the ultraluminous infrared galaxies (ULIRGs) with  $L_{\text{IR}} > 10^{12} L_{\odot}$  (e.g., Arp 220), and the hyperluminous infrared Galaxies (HyLIRGs) with  $L_{\text{IR}} > 10^{13} L_{\odot}$ . While the luminosity range spanned is more than five decades, star formation is the fundamental process in all of these objects. The starbursts that are most amenable to detailed study are obviously the nearest ones, such as M82 (for a detailed analysis see e.g., Förster Schreiber et al. 2001, 2003). These are however low or moderate luminosity objects, and it is not trivial to assess how these objects compare to their higher luminosity, but more distant relatives. This raises the general question how starbursts of different luminosities are related. Two observational facts are directly relevant to this question:

1. higher luminosity starburst galaxies have also higher *star formation efficiencies* (SFEs), as measured by the their infrared luminosity per unit molecular gas mass:  $\text{SFE} = L_{\text{IR}}/M_{\text{H}_2}$ . So more luminous starbursts are also more efficient with their fuel than lower luminosity starbursts (Sanders & Mirabel 1996, and references therein).
2. at the highest luminosities, active galactic nuclei play an increasingly important role, both in frequency of occurrence and in energetic importance (e.g., Veilleux et al. 1995; Kim et al.

---

<sup>★</sup> E-mail: pvdwerf@strw.leidenuniv.nl

**Table 1** Gas Masses, Infrared Luminosities and SFEs for Various Objects

Object	$L_{\text{IR}}$ [ $L_{\odot}$ ]	$M_{\text{gas}}$ [ $M_{\odot}$ ]	SFE [ $L_{\odot} M_{\odot}^{-1}$ ]	References
ULIRGs	few $10^{12}$	few $10^{10}$	$\sim 100$	Sanders et al. (1991)
Milky Way total	$7.4 \cdot 10^9$	$4.9 \cdot 10^9$	1.5	Sodroski et al. (1997)
Milky Way molecular clouds	$2.4 \cdot 10^9$	$1.3 \cdot 10^9$	1.8	Sodroski et al. (1997)
OMC-1 star forming region	$1.2 \cdot 10^5$	$2.2 \cdot 10^3$	54	Bally et al. (1987); Genzel & Stutzki (1989)
Orion BN/KL region	$6 \cdot 10^4$	$1.5 \cdot 10^2$	400	Genzel & Stutzki (1989)

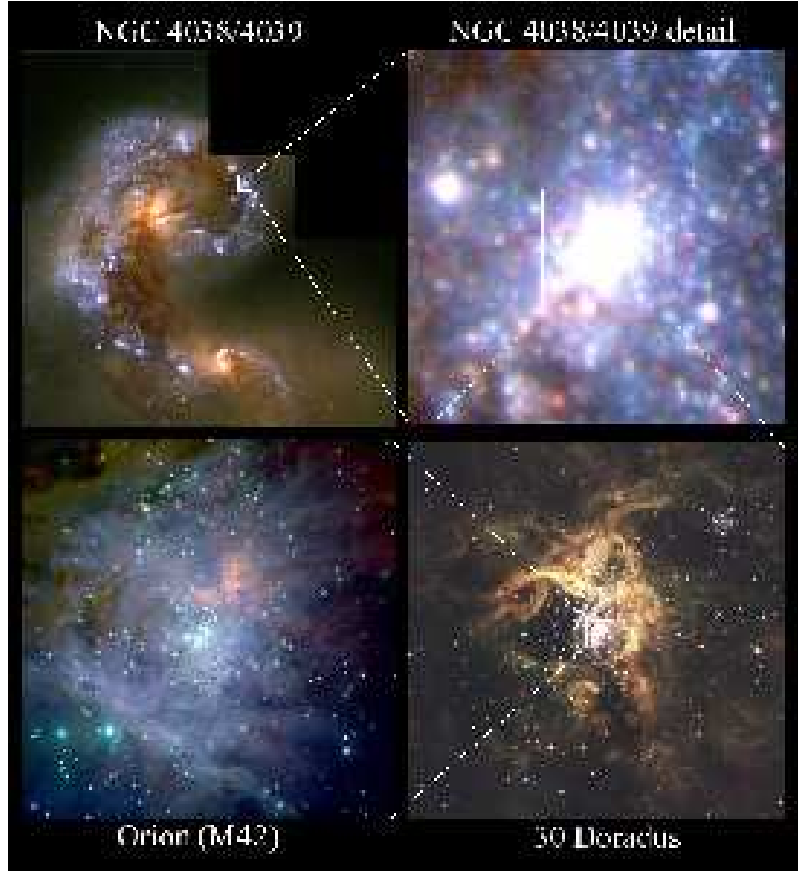
1998); this may point to a causal connection between extreme starbursts and the formation of supermassive black holes.

In order to put the properties of extreme starbursts into perspective, it is instructive to compare their SFEs with those of other objects (see Table 1). It is seen that the SFEs of ULIRGs are comparable to those of the OMC-1 star forming region. In other words, in ULIRGs the *entire* molecular interstellar medium is forming stars at the same efficiency as the OMC-1 region. If the molecular gas mass is overestimated by a factor of 5 with the standard CO-H<sub>2</sub> conversion factor, as argued by Solomon et al. (1997) and Downes & Solomon (1998), the SFEs of ULIRGs even become comparable to the most active region in Orion: the BN/KL massive star formation core.

## 2 EXTREME SUPERSTARCLUSTERS

The question now arises whether young star clusters in starburst galaxies of various luminosities also differ in properties. A characteristic feature of starburst galaxies is the presence of *superstarclusters*, luminous and compact clusters of young stars. It is still a matter of debate whether all stars in starbursts are born in superstarclusters. For instance, Meurer et al. (1995) estimated that only 20% of the ultraviolet (UV) emission from starbursts comes from young compact clusters. This result will certainly be incorrect if young superstarclusters are more obscured than the field population, which is likely the case. A more likely scenario is then that star formation in superstarclusters is the dominant mode in starburst galaxies, and the dissolving clusters give rise to a more diffuse population of young stars (e.g., Mengel et al. 2005).

A compilation of typical properties of star clusters ranging from the extreme to the common is given in Fig. 1 and Table 2. In this table,  $d$  is the total linear size of the cluster as seen in Fig. 1.  $M_*$  is the stellar mass within a fixed radius of 4.5 pc (in the case of [WS99]2, this is a dynamical mass; the other masses are derived from star counts).  $\rho_*$  is the corresponding average stellar mass density within this region, and  $n_{\text{equiv}}$  is the equivalent number density of hydrogen atoms. It is seen that the most extreme superstarclusters are larger in linear dimension, more massive, and have densities similar to those of the cores of star forming molecular clouds, indicating a highly efficient conversion of mass into stars in the most extreme objects.



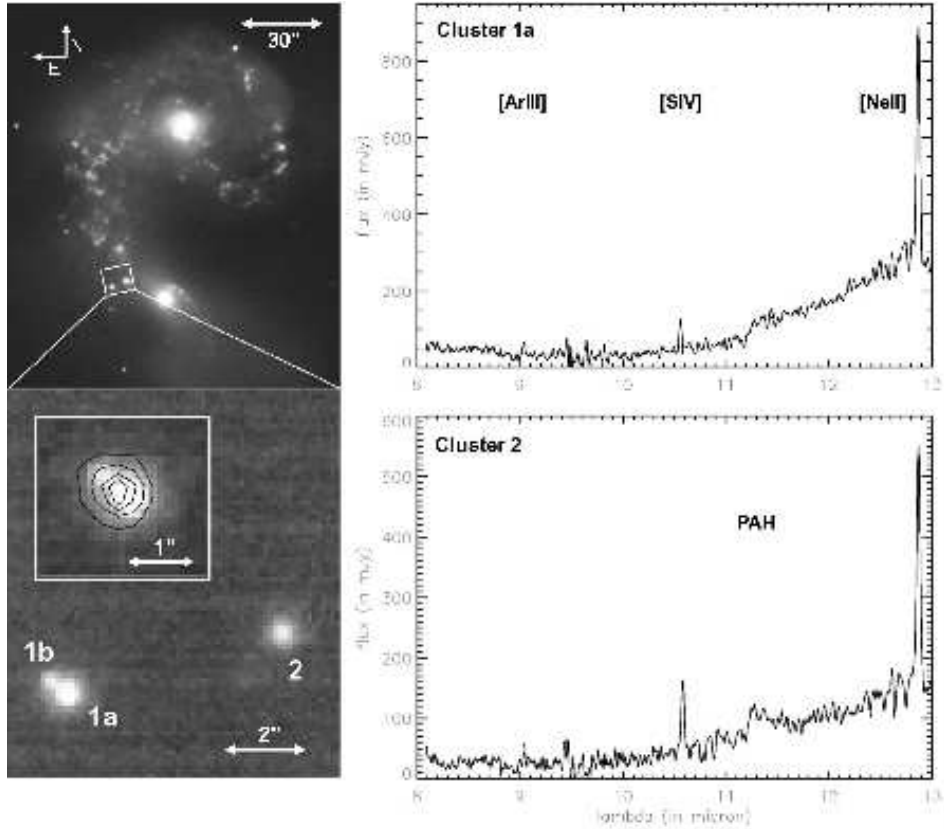
**Fig. 1** Montage illustrating the relative sizes of young starclusters in NGC 4038–4039, 30 Doradus and Orion; see Table 2 for an indication of linear sizes.

**Table 2** Properties of Young Star Clusters in NGC 4038–4039 ([W99]2), 30 Doradus (R136) and Orion (M42)

Object	$d$ [pc]	$M_*$ [ $M_\odot$ ]	$\rho_*$ [ $M_\odot \text{ pc}^3$ ]	$n_{\text{equiv}}$ [ $\text{cm}^{-3}$ ]	References
[W99]2	100	$2 \cdot 10^6$	5200	$1.6 \cdot 10^5$	Mengel et al. (2002)
R136	10	$3 \cdot 10^4$	80	2500	Brandl et al. (1996)
M42	2	1800	5	200	Hillenbrand & Hartmann (1998)

### 3 MID-INFRARED OBSERVATIONS OF THE ANTENNAE OVERLAP REGION

Since stars form in dusty molecular clouds, we may expect young superstarclusters to be optically obscured. This is illustrated dramatically by the Antennae (NGC 4038–4039), where the bolometric luminosity is not dominated by the optically visible star clusters but by a visually obscured, dusty region where the two disks overlap (a region first highlighted as an active star formation site with VLA observations by Hummel & van der Hulst (1986)). The most luminous



**Fig. 2** The VISIR image of the Antennae overlap region in the  $12.8 \mu\text{m}$  [Ne II] filter is shown in the lower left. The inset shows a blow-up of the clusters 1a and 1b, with contours of the emission in the  $11.3 \mu\text{m}$  PAH filter overlaid. The field observed is indicated in the  $K_s$  image on the upper left. Integrated VISIR spectra of two of the clusters are shown on the right-hand side.

cluster in this region produces 15% of the total  $15 \mu\text{m}$  luminosity of the entire Antennae system (Mirabel et al. 1998).

Such superstarclusters are of interest as potentially the youngest simple coeval stellar populations in starbursts and thus furnish excellent tests for the properties of the most massive stars formed in these systems. For sufficiently massive and young superstarclusters, they may offer the opportunity of directly measuring a possible upper mass cutoff of the stellar Initial Mass Function (IMF). Mid-infrared nebular fine-structure lines are excellent probes of such systems, since they are relatively unaffected by dust and can be used to measure the temperature of the ionizing radiation field, and hence the mass of the most massive stars present.

We have recently used VISIR on the Very Large Telescope of the European Southern Observatory at Paranal (Chile) to obtained  $N$ -band ( $8 - 13 \mu\text{m}$ ) data of the two most luminous superstarclusters in the overlap region in the Antennae. Our dataset consists of  $0''.3$  resolution imaging in a number of narrow-band filters in the  $N$ -band, and long-slit spectroscopy with a  $0''.75$  slit. Some key results are shown in Fig. 2.

Inspection of Fig. 2 reveals a few surprising results:

1. the Eastern cluster is separated into two components, separated by approximately  $0''.5$  (50 pc); the brightest of these two (cluster 1a) is slightly resolved; this is cluster [WS95]80 of Whitmore & Schweizer (1995);
2. cluster 1b has no counterpart in any other available dataset; we derive a visual extinction  $A_V > 65^m$  towards this cluster;
3. remarkably, the  $11.3\ \mu\text{m}$  emission shows a different morphology, suggesting a common envelope of emission from hot dust and polycyclic aromatic hydrocarbons (PAHs);
4. comparison with Spitzer-IRS spectra (Brandl, priv. comm.) with a  $5''$  slit reveals that  $\gtrsim 50\%$  of the  $12\ \mu\text{m}$  continuum is detected in the  $0''.75$  VISIR slit; however, the equivalent width of the  $11.3\ \mu\text{m}$  PAH feature in the VISIR data is much smaller than in the larger aperture Spitzer spectra;
5. both clusters exhibit emission in the  $10.5\ \mu\text{m}$  [SIV] line, an ionization stage requiring 34.8 eV (while the  $12.8\ \mu\text{m}$  [NeII] lines requires only 21.6 eV); in particular in cluster 2 the [SIV]/[NeII] ratio in our data is higher than in larger aperture Spitzer data, significantly affecting the interpretation of the results.

The low equivalent width of the PAH emission indicates that the PAH emission is not preferentially excited by the superstarclusters, but is dominated by more diffuse emission, excited by the softer UV radiation from more widespread young stars of slightly later type. The PAH emission is therefore not a good tracer of the most recent star formation, and may provide a better measure of the star formation integrated over a somewhat longer timescale.

A simple analysis of the [SIV]/[NeII] ratio in cluster 1a indicates a radiation field corresponding to an O3 star; comparison with the total luminosity of this cluster then requires approximately 1000 of such stars to be present. This result may reveal a real absence of stars more massive than O3; alternatively, earlier spectral types could still be present if they are formed in ultracompact HII regions, of which the emission lines are strongly quenched. A more detailed analysis of these results is in preparation (Snijders et al.).

**Acknowledgements** It is a pleasure to thank the organisers for this thoroughly enjoyable meeting.

## References

- Bally, J., Stark, A. A., Wilson, R. W., & Langer, W. D. 1987, *ApJ*, 312, L45
- Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Hofmann, R., Loewe, M., & Quirrenbach, A. 1996, *ApJ*, 466, 254
- Downes, D. & Solomon, P. M. 1998, *ApJ*, 507, 615
- Förster Schreiber, N. M., Genzel, R., Lutz, D., Kunze, D., & Sternberg, A. 2001, *ApJ*, 552, 544
- Förster Schreiber, N. M., Genzel, R., Lutz, D., & Sternberg, A. 2003, *ApJ*, 599, 193
- Genzel, R. & Stutzki, J. 1989, *ARA&A*, 27, 41
- Hillenbrand, L. A. & Hartmann, L. W. 1998, *ApJ*, 492, 540
- Hummel, E. & van der Hulst, J. M. 1986, *A&A*, 155, 151
- Kim, D.-C., Veilleux, S., & Sanders, D. B. 1998, *ApJ*, 508, 627
- Mengel, S., Lehnert, M. D., Thatte, N., & Genzel, R. 2002, *A&A*, 383, 137
- . 2005, *A&A*, 443, 41
- Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, *AJ*, 110, 2665
- Mirabel, I. F., Vigroux, L., Charmandaris, V., Sauvage, M., Gallais, P., Tran, D., Cesarsky, C., Madden, S. C., & Duc, P.-A. 1998, *A&A*, 333, L1

- Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J., & Soifer, B. T. 2003, *ApJS*, 126, 1607
- Sanders, D. B. & Mirabel, I. F. 1996, *ARA&A*, 34, 749
- Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, *ApJ*, 370, 158
- Sodroski, T. J., Odegard, N., Arendt, R. G., Dwek, E., Weiland, J. L., Hauser, M. G., & Kelsall, T. 1997, *ApJ*, 480, 173
- Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, *ApJ*, 478, 144
- Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, *ApJS*, 98, 171
- Whitmore, B. C. & Schweizer, F. 1995, *AJ*, 109, 960